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Report No. 53940

# ~~THE~~ NONDESTRUCTIVE EVALUATION OF LOW DENSITY FOAM-ALUMINUM COMPOSITE MATERIALS

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16. ABSTRACT

NOPCO BX-250, a polyurethane spray foam is now used as cryogenic insulation for S-II stages of the Saturn vehicle. This application has required considerable effort in the development of nondestructive methods to evaluate the mechanical integrity of foam to metal bonds. Certain inspection problems associated with low density foam-aluminum composites are evaluated in this report. The development of audio frequency methods required to overcome these difficulties are described. Additional effort was required to adapt one of these audio frequency methods and to develop radiographic techniques for the detection of voids in the foam. The complementary nature of these void detection methods is shown. All of the methods are thoroughly discussed. They are illustrated with numerous drawings, photographs, and radiographs to clearly show their current value to the Saturn program and their potential for other applications.

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# THE NONDESTRUCTIVE EVALUATION OF LOW DENSITY FOAM-ALUMINUM COMPOSITE MATERIALS

## SUMMARY


Efforts to improve the quality of cryogenic insulation for use on the S-II stage of Saturn vehicles led to the use of NOPCO BX-250, a polyurethane spray foam which is much lighter and has better thermal properties than previously used insulation, but the necessity for determining bond integrity still exists. Standard ultrasonic instrumentation is inadequate for determining bond integrity, so considerable effort has been required to develop nondestructive methods for evaluating the mechanical integrity of foam-to-metal bonds.

The major difficulty in detecting lack of adhesion between NOPCO and aluminum with ultrasonic techniques is due to the low acoustic impedance of the foam. More specifically, the acoustic characteristics of this foam and of air are too nearly the same. There isn't enough difference between the magnitude of energy reflected from the aluminum-foam interface when a bond exists and that reflected from the aluminum-air interface when there is no bond to allow the use of pulse echo testing. This and other inspection problems associated with low density foam-aluminum composites are evaluated in this report.

The development of audio frequency methods required to overcome these difficulties are described. The first method developed utilizes a special transducer called, "A Resonant Foam Coupler." This device is applied to the foam side of the composite. It detects lack of bond by sensing changes in vibrational characteristics of the specimen caused by debonds. Through-transmission audio frequency techniques have also been established which have the capability of detecting lack of bond and of detecting voids in the foam. No couplant is required since vibrations are induced into the metal electrically. Additionally, experiments have demonstrated that film radiography can be used to detect voids in low-density foam-aluminum composite materials.

# INTRODUCTION

Cryogenic insulation of early S-II stages of the Saturn vehicle consisted of phenolic honeycomb core filled with foam. Currently, NOPCO BX-250, a polyurethane spray foam is used. Thermal properties, weights, and manufacturing considerations pertinent to the two types of insulation are compared in Table 1. This comparison clearly shows the advantages of the polyurethane foam insulation.

TABLE 1. FOAM FILLED PHENOLIC HONEYCOMB CORE VERSUS POLYURETHANE FOAM INSULATION

| Property | Property Advantages | | Spray Foam |
|---|---|---|---|
| | Requirements | Foam Filled Phenolic Honeycomb Core | |
| K Factor | | 0.75 | 0.12 |
| Boil-Off | 6% per hr Max | 5.5% | 3.0% |
| Heat Leak | 215 000 Btu Max | 180 000 Btu | 130 000 Btu |
| Required Thickness | | 1.6 in. | 0.75 in. |
| Weight | | 5400 lb | 3200 lb |
| **Other Advantages** | | | |
| Ease of Manufacture | | | |
| Less Expensive (Basic Material and Manufacturing) | | | |
| Minimum Amount of Repairs Required | | | |
| Ease of In-Process Repair | | | |
| No Helium Purge | | | |

The nondestructive evaluation of this low density foam-aluminum composite material presents a difficult problem since standard ultrasonic technology is inadequate for detecting lack of adhesion between the foam and aluminum. Perhaps the basic limitations of conventional methods and instrumentation are not readily apparent, so a brief review of applicable acoustic fundamentals will be followed by a detailed discussion of these limitations and of methods being developed to overcome them. The following formulas are useful:

$$R = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 \tag{1}$$

$$Z = PV \tag{2}$$

where

$P$ = Density ($gm/cm^3$)

$Z$ = Acoustic impedance ($gm/cm^2$-sec)

$Z_1$ = Acoustic impedance in first medium

$Z_2$ = Acoustic impedance in second medium

$R$ = Reflection coefficient

$V$ = Velocity (cm/sec)

When sound travels from one medium to another the percentage of energy reflected from the boundary is determined by the relative acoustic impedance of the two mediums as shown in formula (1). No energy will be reflected when an ideal bond exists between two materials having the same acoustic impedance. Thus, the magnitude of sound reflected from a boundary is a function of relative acoustic impedance values and of bond conditions existing between the two materials. The major difficulty in detecting lack of adhesion between NOPCO and aluminum is due to the low acoustic impedance of the foam. To be more specific, the acoustic characteristics of this foam and of air are too nearly the same. There is not enough difference between the magnitude of energy reflected from the aluminum-foam interface, when a bond exists, and that reflected from the aluminum-air interface when there is no bond to allow the use of pulse echo testing. As an illustration, numerical values for the acoustic characteristics of NOPCO and of air have been taken from Table 2 and inserted in formula (1) which is:

$$R = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\right)^2 \quad .$$

For the aluminum-air interface,

$$R = \left(\frac{1.75 - 0.000042}{1.75 + 0.000042}\right)^2 \cong 0.998 \quad ,$$

and for the aluminum-NOPCO interface,

$$R = \left(\frac{1.75 - 0.00193}{1.75 + 0.00193}\right)^2 \cong 0.993 \quad .$$

TABLE 2. SELECTED ACOUSTIC PROPERTIES

| | Velocity ($cm/sec \times 10^5$) | Acoustic Impedance ($gm/cm^2$-$sec \times 10^6$) | Wavelength at 1 MHz (cm) | Density ($gm/cm^3$) |
|---|---|---|---|---|
| Aluminum | 6.25 | 1.75 | 0.625 | 2.800 |
| Air | 0.357 | 0.000042 | 0.0357 | 0.0018 |
| Plastic (Acrylic Resin) | 2.67 | 0.32000 | 0.264 | 1.180 |
| NOPCO | 0.49 | 0.00193 | 0.048 | 0.0395 |
| Water | 1.49 | 0.14900 | 0.149 | 1.000 |

Thus, it is readily apparent that the pulse echo method is marginal for evaluating this type of composite. An experimental verification of this was obtained by using commercial ultrasonic instrumentation and the composite panel shown in Figure 1. The mylar cover kept water out of the space where the foam had been removed to allow positive simulation of debond conditions. Oscilloscope traces of reflections from defective and from good insulation are shown in Figure 2. These reflections were obtained with a high resolution ultrasonic system. Numerous reflections are required before any significant amplitude change occurs. Only the difference in exponential damping of these reflectors allows detection of this "ideal debond." Even this limited-flaw detection capability requires water coupling and very careful instrumentation adjustments. It is considered impractical for evaluating large areas of cryogenic insulation. So, as predicted mathematically, the pulse echo technique is marginal for this particular application.

NOPCO foam attenuates high frequency energy so much that through-transmission ultrasonic testing is impractical with available instrumentation. Thus, as previously stated, standard ultrasonic technology is inadequate for detecting lack of adhesion between the layers of this composite material. Obviously, new or modified old methods are required to achieve program objectives. These objectives are as follows:

1. The development of methods for detecting lack of adhesion between the low density spray foam and metal.

2. To detect, if practicable, debonds in composites when only one side of the material is accessible.

3. To develop methods of detecting voids in foam that is attached to metal.

4. To make all instrumentation required for these tests compatible with available scanning and recording systems.

All of these objectives have not been achieved. However, several audio frequency methods of nondestructively evaluating bond conditions in the insulation have been developed and evaluated. Radiography and through-transmission sonic methods have been used to detect voids in the foam. Theory of these methods, experimental apparatus, and test results, are described in this report.

# PROCEDURES

## The Resonant Foam Coupler

Conventional ultrasonic instruments use high impedance transducers which can only be used to introduce sound into the metal face plate of composite materials. The presence or absence of low density foam has little effect on this vibrating metal. However, if vibration at audio frequencies could be effectively introduced into the NOPCO foam, the presence of dense, rigid metal would certainly modify the vibrational pattern of the low density foam. Low frequencies must be used since the foam pronouncedly attenuates ultrasonic frequencies. Thus, the problem becomes a matter of matching the acoustic impedance of the foam to some type of low frequency transducer. An obvious coupling medium is foam of the type used in the composite. As shown in the introduction, less reflection occurs at a boundary when materials have the same acoustic impedance. Thus, smaller reflections mean better energy transfer. Several possible transducer configurations were considered during the initial planning stage of this program. A picture of the first useful design is shown in Figure 3. The cone of a commercial loudspeaker is adhesively bonded to the foam coupler. This speaker, energized with an ordinary audio oscillator, is an effective instrument for getting sound into the coupler and into the composite material. A contact microphone placed in the lower portion of the coupler detects changes in vibrational patterns caused by debonds in the specimen. The signal developed by the microphone is amplified, processed, and displayed on a spectrum analyzer oscilloscope. Major components of the complete system are illustrated in Figure 4. Indications obtained from a debond and from a well bonded area of a composite panel are shown in Figures 5a and 5b respectively. The center indication in both pictures is simply the center frequency to which the spectrum analyzer system has been set. The frequencies above and below this center frequency are used as indicators of bond conditions. Debonded foam has greater freedom of motion than well bonded material. An operating frequency is selected to emphasize this. Thus, a debond causes a large increase in vibrational energy of the entire system which includes the speaker, the coupler, and the foam of the specimen.

Although speakers can be used as sources of low frequency mechanical energy, certain application limitations exist. The most critical limitations are fatigue of the speaker cone material and poor vibrating characteristics of the system when the resonant foam coupler is placed in a horizontal position. So, the speaker was replaced with a coil and a permanent magnet combination. The magnet, imbedded in the foam coupler, reacts with the induction field generated by an energized coil to produce motion. A photograph and a cross sectional view of this modified resonant foam coupler are shown in Figures 6 7 respectively. Although this coupler is more reliable than the one using the speaker, more power is required. An amplifier is used to increase the signal from the oscillator before it is applied to the transducer (Fig. 8). Figure 9 shows all of the experimental apparatus. The imbedded magnet distorts vibrational characteristics of the resonant system and results in a more complex pattern than is obtained with the speaker system. This is clearly shown in Figure 10. The improved resonant foam coupler system overcomes most of the limitations of the speaker-type transducer and can be used in the laboratory to detect debond conditions in low density foam-aluminum composites provided the specimen is in a horizontal position. The pressure necessary to hold the transducer against a specimen that is in the vertical position can cause misleading indications. In spite of these difficulties, the resonant foam coupler is considered a significant development. The pressure problem can be overcome and the basic system has potential for other applications.

## Methods of Debond Detection that Utilize Electromagnetically Induced Vibration

It is highly improbable that a single method could be used to evaluate bond conditions in composite materials having all foam-metal thickness combinations of interest to this Center. Furthermore, as stated in the introduction, means of adapting debond detection instrumentation to available scanning and recording systems is desirable. Although the resonant foam coupler is a useful transducer, it is essentially a manually operated device having mechanical limitations for field type testing. So, to determine the most practical procedure for evaluating cryogenic insulation expeditiously, a concurrent development program is being used to develop electromagnetic or eddy current techniques for introducing vibration into the metal. Through-transmission and single-side methods are being developed, but only details of the through-transmission technique will be described in this status report.

For debond detection a low frequency motion induced in the metal with a coil-type vibrator is easily transmitted to the foam. Variations, caused by bond conditions, in the magnitude of motion transmitted to the foam are detected with a contact microphone. Figures 11 and 12 show details of experimental apparatus used for this through transmission testing. A low voltage audio signal is obtained from a commercial oscillator; amplified and applied to the vibrator. Complicating factors of acoustic impedance and reflected energy percentages are less significant with this approach than with ultrasonics. More specifically, the interface between the metal and foam will support both tension and compression when a good bond exists. When there is no bond, only compressive forces can be transmitted through the interfaces. This results in a significant decrease in sound to the microphone.

Careful selection of the operating frequency with respect to foam properties and to foam and metal thickness combinations is required for effective debond detection. The most practical method of selecting optimum operating frequencies is to make frequency versus amplitude scans on simulated debonds and on areas of the specimen that are well bonded. It is advisable to select several areas that are apparently well bonded and to prove the point by destructive testing subsequent to obtaining the frequency scans. Typical low audio frequency versus amplitude scans are shown in Figure 13. A test frequency was selected from these scans by observing the frequency having the greatest ratio of good bond to debond signals. About 300 Hz is best for this low audio frequency range. Subsequent to frequency selection, vibration signals picked up with the contact microphone were amplified, processed, and displayed on the oscilloscope of a spectrum analyzer. Oscilloscope indications of debond and good bond conditions are shown in Figures 14a and 14b, respectively.

Frequencies of only 200 or 300 Hz require very little energy to penetrate composite materials. Less than 1 watt of power to the vibrator was required to obtain the indications of Figure 14. However, the foam attenuates higher audio frequencies rapidly. About 15 watts, or more specifically, 15 volt-amperes to the vibrator coil is required to transmit an adequate amount of energy at 5 kHz through 1 inch of the NOPCO foam. High audio frequency, high energy scans of composite transmission characteristics are plotted in Figures 15 and 16. The variation of attenuation with frequency is obvious. This amount of power to the vibrator caused saturation of the recording device at the lower frequencies. However, the significant peak to observe is near 5 kHz in Figure 15. This is a scan of a well bonded panel. Figure 16, a scan of a defective specimen, clearly shows the reduction of the selected peak by a 3-inch debond. Subsequent to selecting this optimum frequency, a spectrum analyzer was used to eliminate the unnecessary indications at other frequencies. This is illustrated in Figure 17. The time base of the analyzer was expanded for this frequency, so only one peak of the usual double peak presentation is shown.

In general, the highest frequency having a large signal ratio for well bonded material to debonded areas is the logical frequency to use. Although debonds can be detected at lower audio frequencies, better defect resolution is obtained with higher frequencies.

In summary, debonds can be nondestructively detected in cryogenic insulation of the S-II type with a through-transmission eddy current system. Although this can be done in a reliable manner, only spot tests can be made with available instrumentation. The original objectives of this program included:

1. The development of methods to test cryogenic insulation with all instrumentation located on a single side.

2. To adapt the new techniques to available scanning and recording systems.

The eddy current method of vibrating metal has great potential for "single-side" testing. Debonds have been detected in laboratory specimens with the vibrator and the vibration detector located on the foam side of a composite panel. An improved transducer design and more audio power would increase the reliability of this single side technique. Furthermore, since electrically induced vibration requires no specimen contact, and noncontacting means of detecting changes in motion is feasible, this basic method has rapid scanning and recording potential.

## Void Detection Methods

The question of whether or not a bond exists between foam and aluminum of composite panels is considered more critical than the possibility of having a few voids in the foam. Accordingly, most of the effort devoted to this cryogenic insulation evaluation program has been directed to the development of methods of nondestructively detecting lack of bond between layers of the composite. This was a fortunate priority choice since the high audio frequency through transmission method developed for detecting lack of bond has also shown potential for detecting voids in the foam. Furthermore, experiments have demonstrated that radiographic methods are also useful for this purpose. Although X-radiation must pass through both foam and aluminum, very small voids in foam can be detected. Details of these methods will be discussed in subsequent paragraphs.

## An Audio Frequency Method of Void Detection

The through-transmission audio frequency method can be used to detect voids in low density foam-aluminum composites. Of course, there is nothing new about the general theory of through-transmission testing whether ultrasonic or audio frequency energy is used. The problem is simply a matter of selecting effective methods of introducing sound into the specimen and of detecting changes in transmitted energy caused by imperfections in the material. This involves impedance matching, frequency selection, and energy level determinations. These factors have already been discussed and repetition here is unnecessary. The experimental apparatus shown in Figure 11 was also used to detect voids. Simulated defects were made by drilling 0.25-inch diameter holes in the edge of a composite panel. The effect of these holes on the amount of transmitted energy is illustrated in Figure 18. Maximum sensitivity to voids occurred when the longer dimension of the contact microphone was aligned parallel to the length of the hole. The microphone is about 0.75 inch wide by 2 inches long. Obviously, the use of a smaller vibration detector would increase the sensitivity of the method and allow the detection of smaller voids.

# Radiographic Detection of Voids

Since the time low-density-spray foam-aluminum composites were first considered as insulation for S-II stages of Saturn, numerous methods of void detection have been discussed by personnel in the materials evaluation field. Microwave, neutron radiography, lower frequency ultrasonic, thermal, and several other methods have been considered. But, apparently no one considered the possibility of using conventional radiography until recently. There is little doubt that high frequency microwaves and neutron radiography could be used to detect voids in foam-aluminum composites. However, the field type applications of microwave methods could prove difficult and neutron radiography is very expensive and time consuming. Furthermore, some of the other methods are not without merit. But why consider buying expensive systems without first determining the capability of available instrumentation?

Although aluminum is many times as dense as foam, the foam used in the S-II type insulation is thick compared to the metal. Thus, it was theorized that rather large voids in the foam would increase the X-radiation transmitted through the material enough to be detected with sensitive film. Experiments verified this. In fact, radiographic techniques have been developed having much greater sensitivity to small voids than had been expected. Details of this work are described in subsequent paragraphs.

Simulated defects were made in small blocks of NOPCO foam 1 inch thick by drilling a series of holes 0.063, 0.090, and 0.150 inch in diameter. A hole of each diameter was drilled 0.90, 0.150, and 0.200 inch in depth. These blocks were X-rayed as they were placed in turn on plates of 2014-T6 aluminum 0.063, 0.125, and 0.188 inch thick. The X-ray machine used for this work was an MG-150 Norelco with the "F" X-ray tube having a 0.7-mm focal spot. The kilovoltage range is 25 to 75 kVp and the film focal distance (ffd) was 40 inches for all of the radiographs made in this experiment. Kodak type "m" film, having very fine grain, and an X-Omat automatic film processor were used for this work. The current was held constant at five milliamperes as only the voltage was changed to compensate for changes in metal thickness. Details of radiographic techniques used for the various foam-metal thickness combinations are given in Table 3. These techniques produced an optimum film density of 2.40 and 2.80. Previous work at this Center had demonstrated that this radiographic film density range is best for locating small discontinuities.

TABLE 3. RADIOGRAPHIC TECHNIQUES FOR VOID DETECTION

| Specimen (1-in. Foam) | Voltage (kV) | Current (ma) | Time (sec) | Film Focal Distance (in.) | Type Film |
|---|---|---|---|---|---|
| No Metal | 25 | 5 | 120 | 40 | "m" |
| 0.063-in. 2014-T6 Al | 32 | 5 | 120 | 40 | "m" |
| 0.125-in. 2014-T6 Al | 40 | 5 | 120 | 40 | "m" |
| 0.188-in. 2014-T6 Al | 45 | 5 | 120 | 40 | "m" |

Radiographs of simulated defects in cryogenic insulation are shown in Figure 19. This work clearly demonstrates that radiography can be used to detect voids in the S-II type insulation although X-radiation must pass through metal as well as the foam. Voids in foam as small as 0.125 inch in diameter by 0.150 inch deep can be detected through 0.188-inch aluminum. Thus, radiographic sensitivity to small voids is more than adequate for this particular material.

Acoustic and radiographic methods of detecting voids in cryogenic insulation are complementary to each other. Radiography is very sensitive to small defects when metal face plates are rather thin. It is also useful to evaluate questionable areas of debond that were first located by other means. The through-transmission eddy current method has more potential for inspecting composites having thick metal face plates.

## CONCLUSIONS

While all of the objectives of this experimental program have not been fully attained, significant progress has been made. Low density foam-aluminum composites can be nondestructively evaluated by making numerous spot determinations of bond conditions and of void locations. Lack of bond between the foam and metal can be detected in laboratory specimens with the resonant foam coupler. Debonds can also be detected with audio frequency through transmission techniques. Voids in the foam can be found with radiographic and with low frequency transmission methods. In addition to these developments, program objectives are:

1. To accomplish these evaluations when access is limited to one side of a structure.

2. To make all new instrumentation required for these tests compatible with available scanning and recording systems.

The resonant foam coupler requires access to only the foam side of composites and can, with certain improvements, be used for field type testing. Experiments have also shown that electrical vibrators and vibration detectors located on the same side of a specimen can be used to detect lack of bond, but more work is required to make the system practical. Subsequent to improving the electrical vibration system, which is noncontacting, and the selection of a suitable noncontacting microphone, no difficulty is expected in adapting these debond detection systems to available scanners and recorders.

Finally, the audio frequency through-transmission method is recommended for immediate application to the Saturn program. This will enable the evaluation of selected spots in a reliable manner. Radiography and the audio frequency method are recommended for the detection of voids. These methods are complementary to each other.

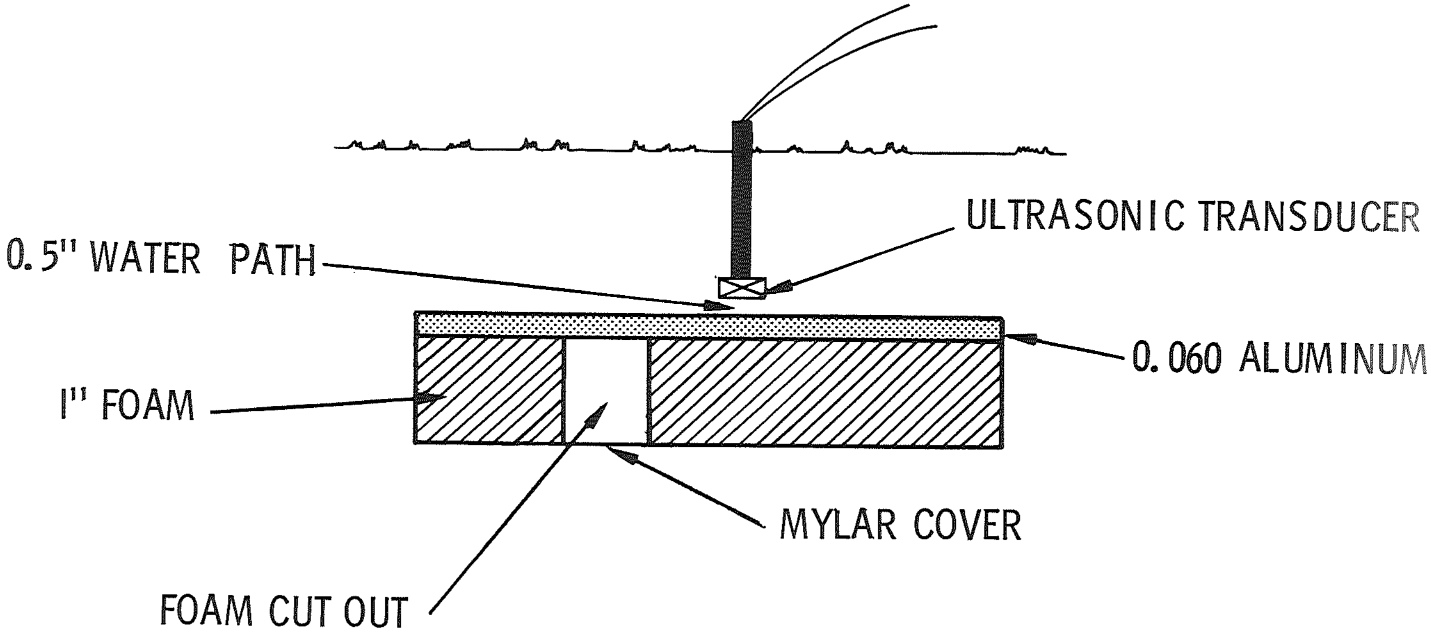
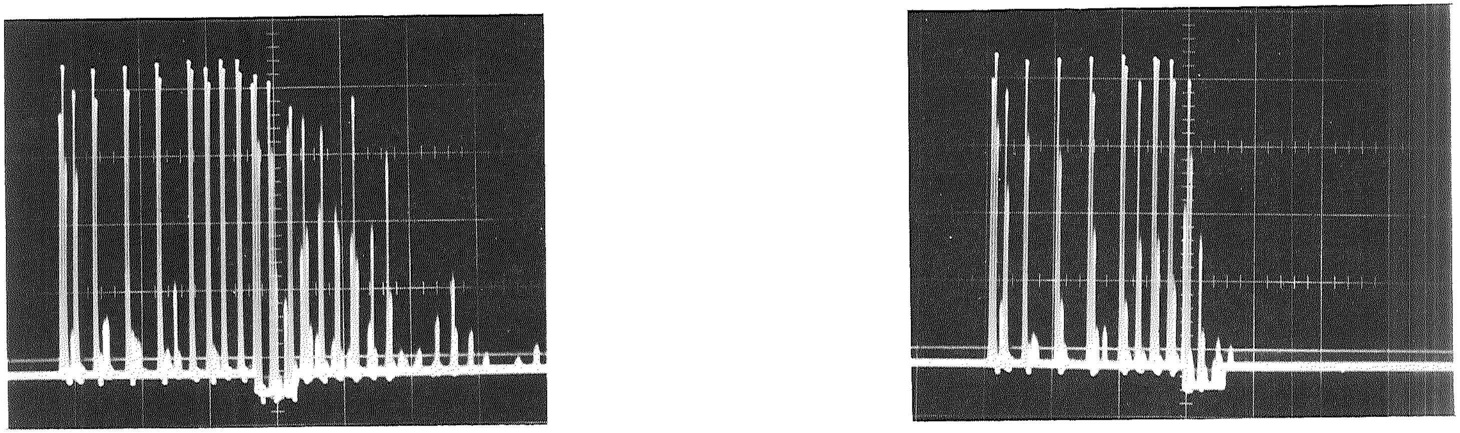



Figure 1. Method of comparing aluminum-foam and aluminum-air interface reflections.



(a)
Removed Foam

(b)
Good Bond

Figure 2. Reflections from aluminum-air and from aluminum-foam interfaces

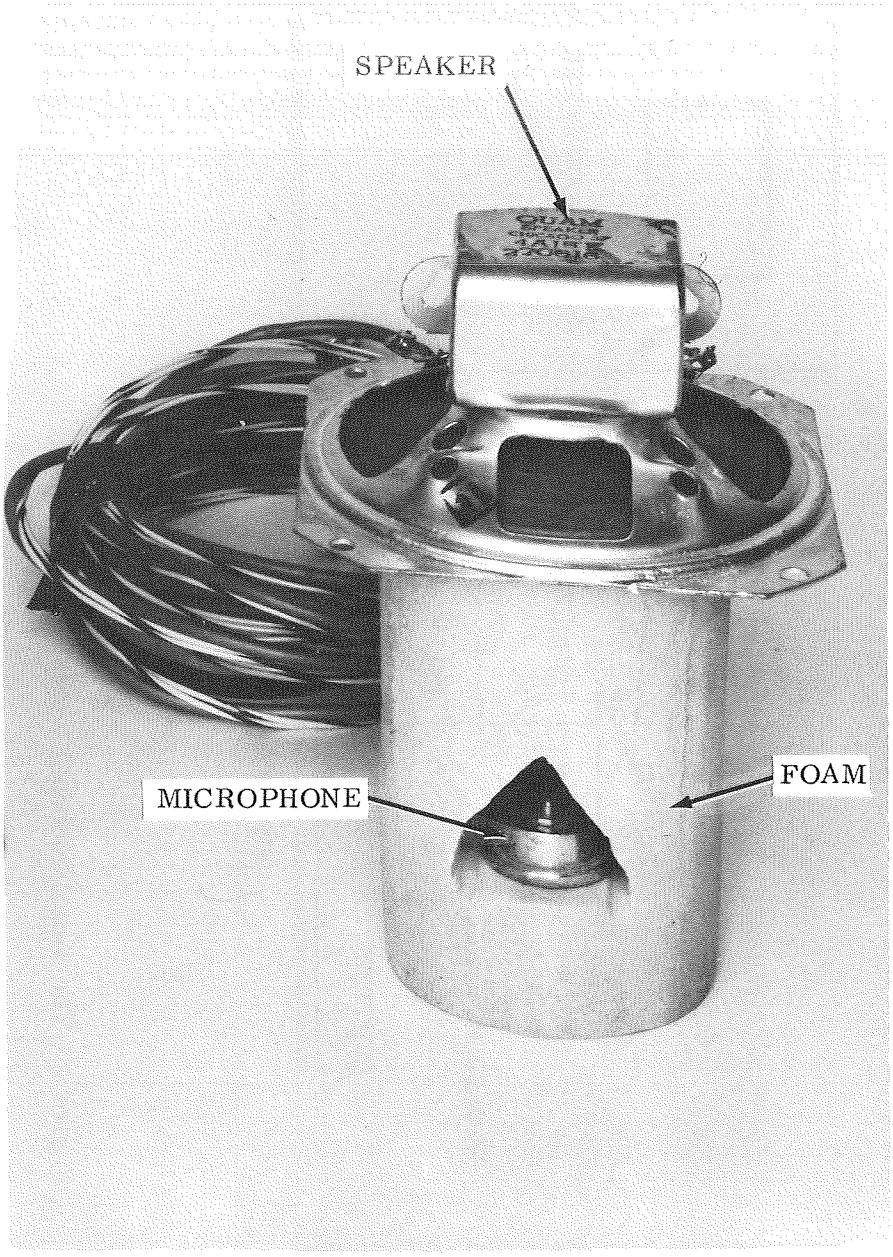



Figure 3. The resonant foam coupler.

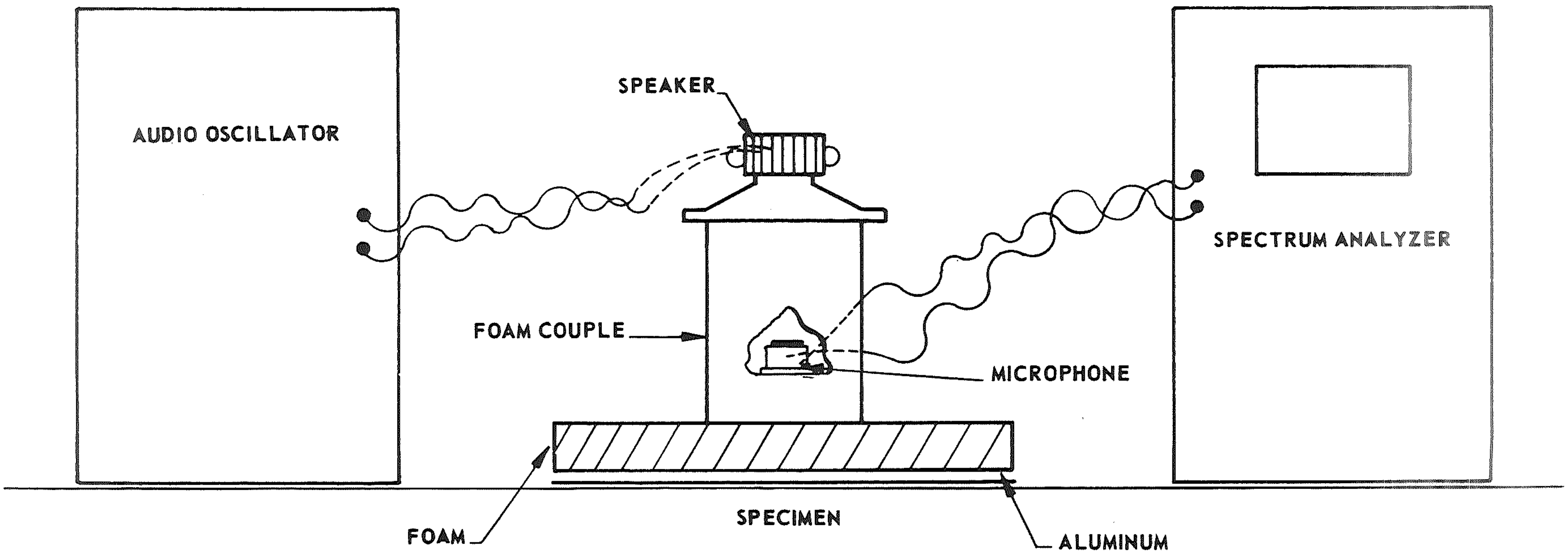
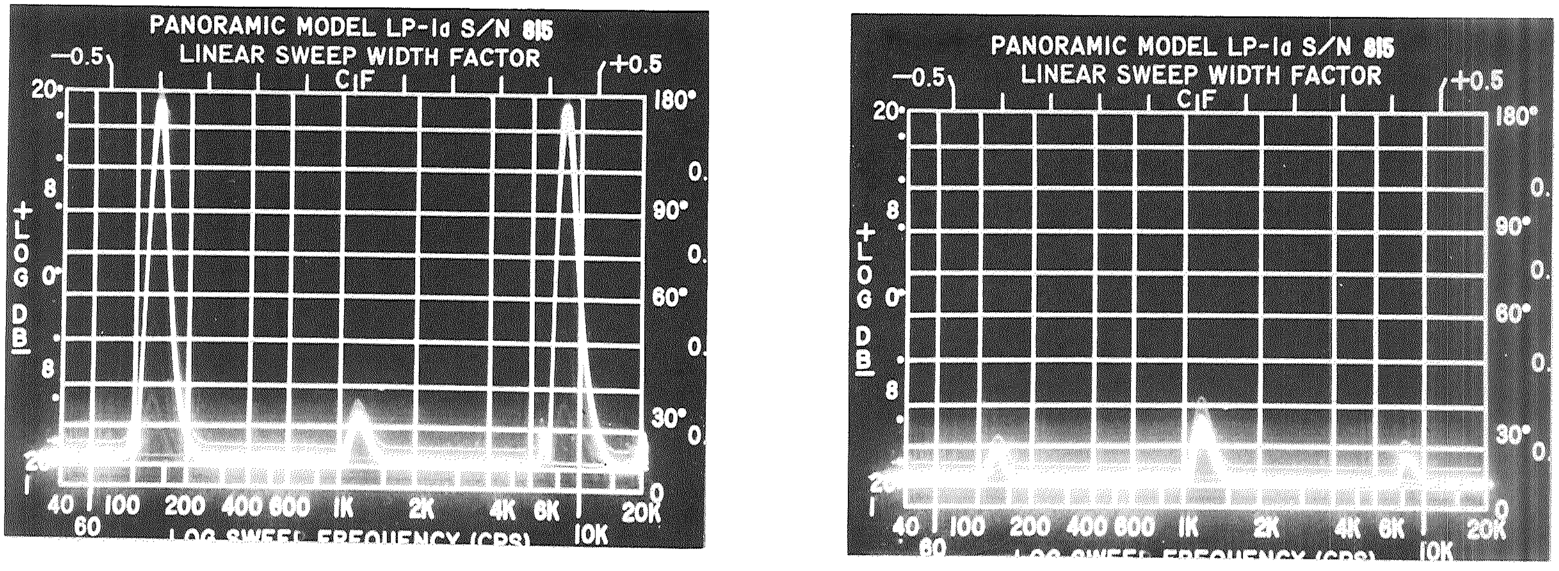



Figure 4. The initial resonant foam coupler system.




(a)
Debond

(b)
Good Bond

Figure 5. Bond condition indications obtained with the resonant foam coupler.

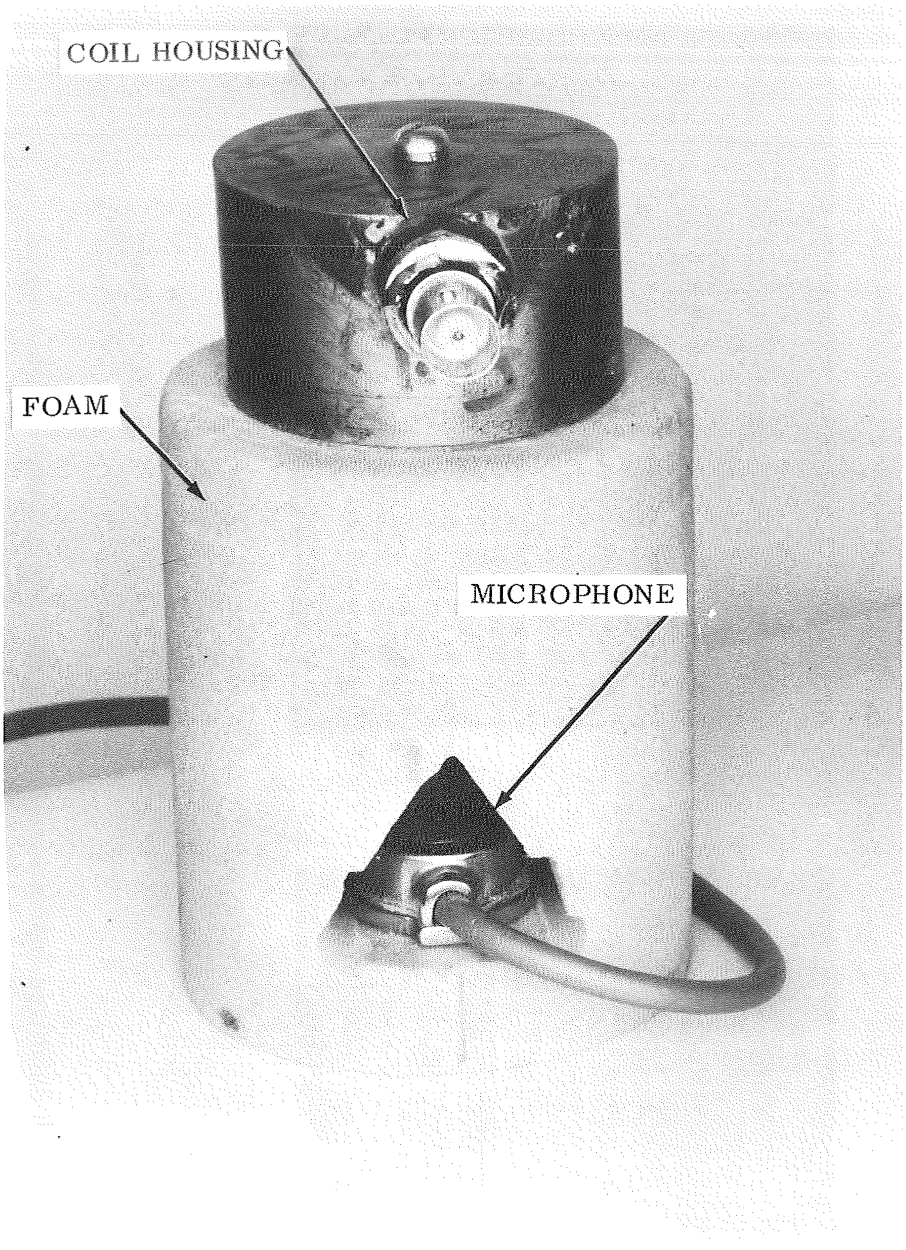



Figure 6. An improved resonant foam coupler.

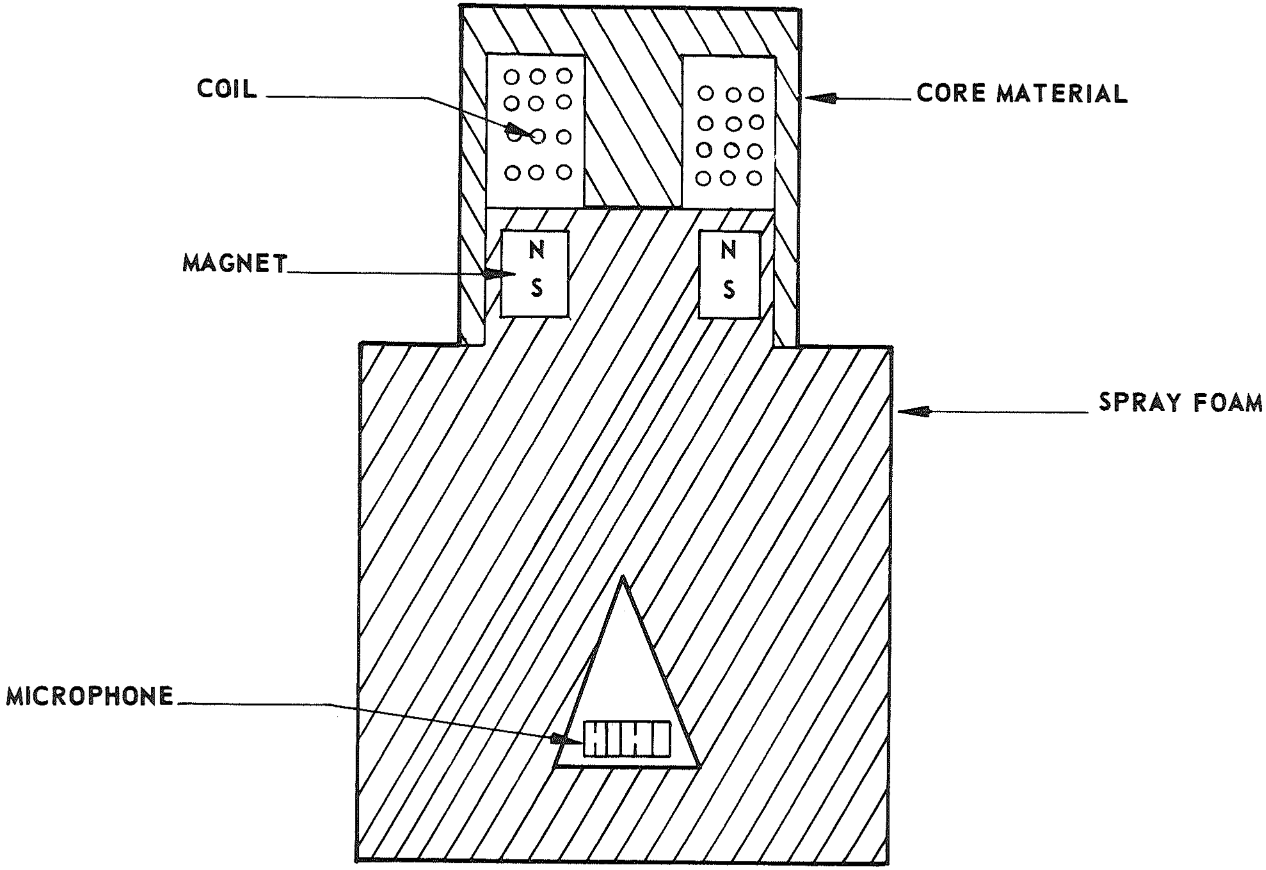



Figure 7. Construction details of an improved resonant foam coupler.

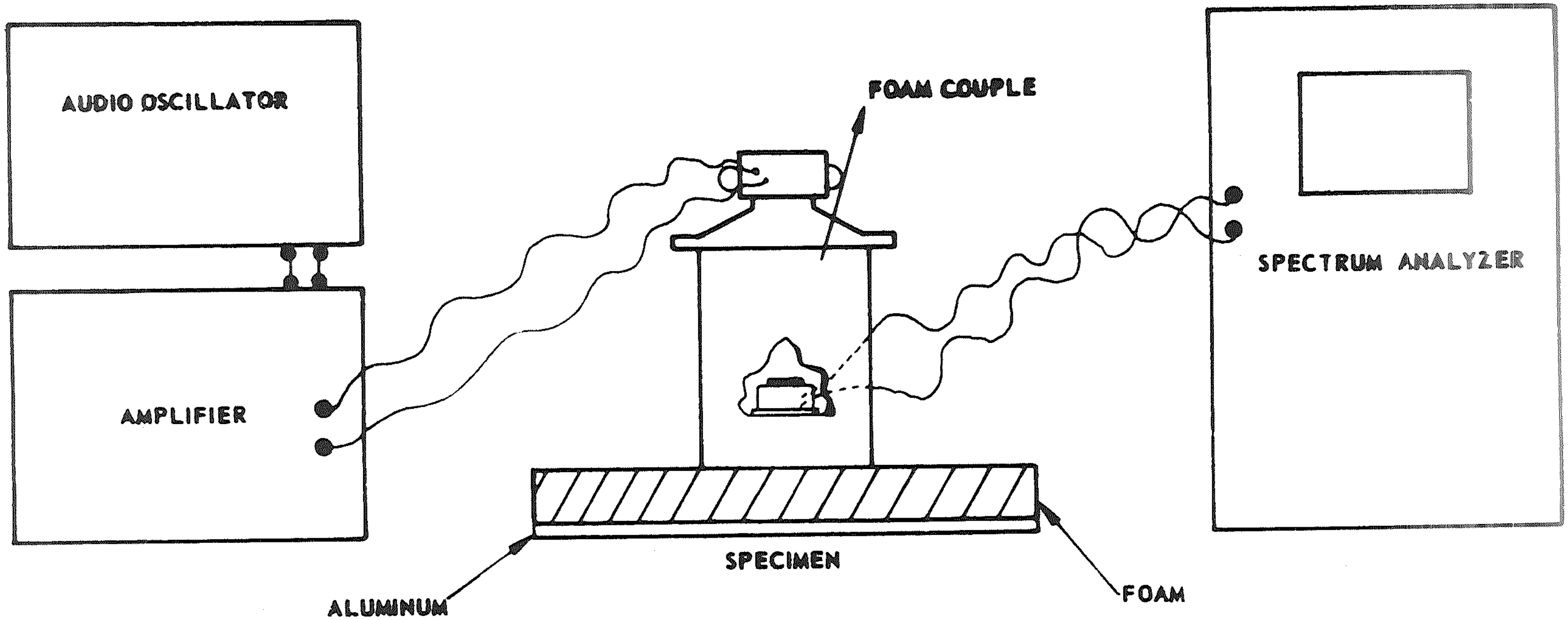



Figure 8. Details of an improved resonant foam coupler system.

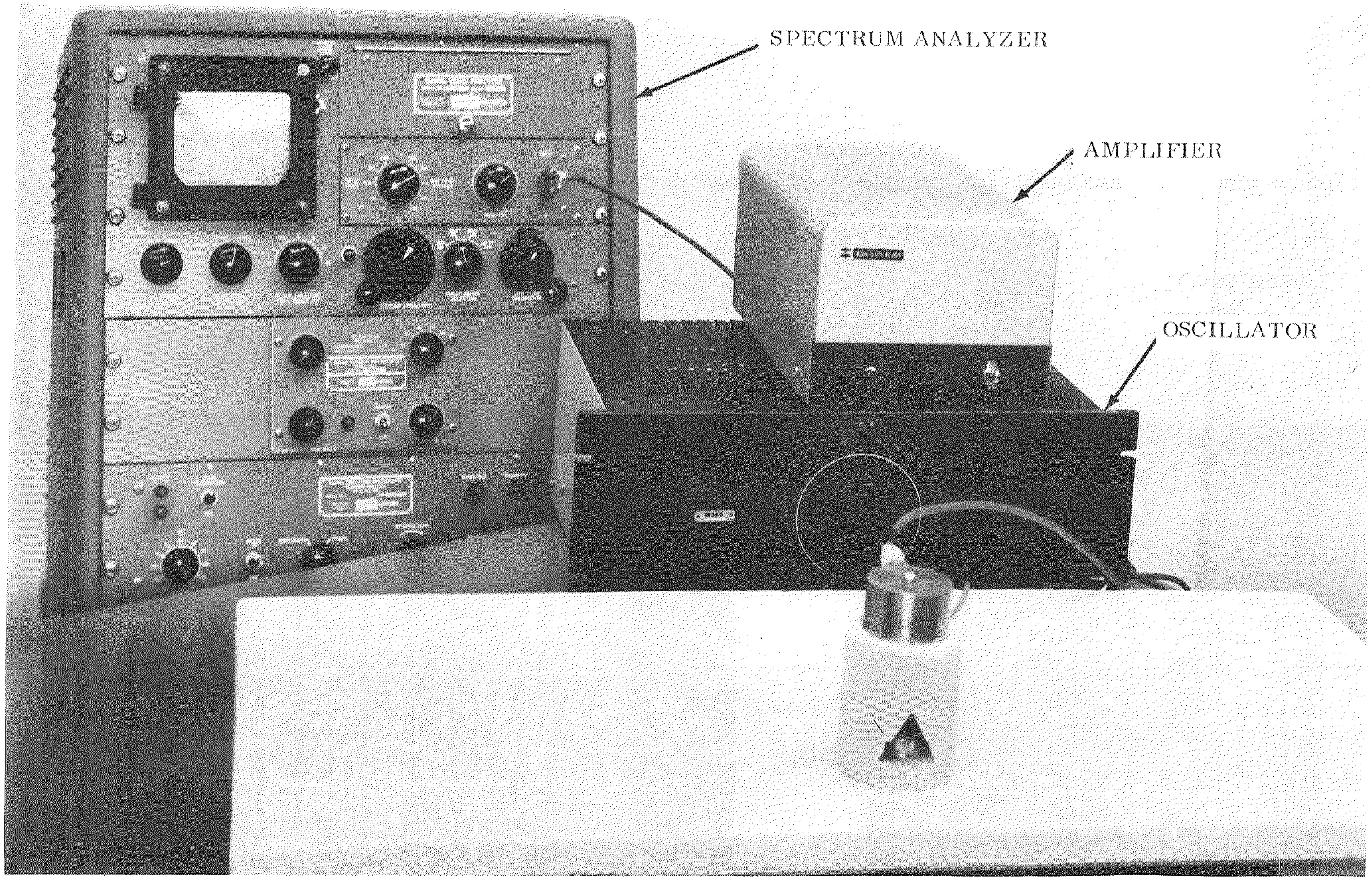
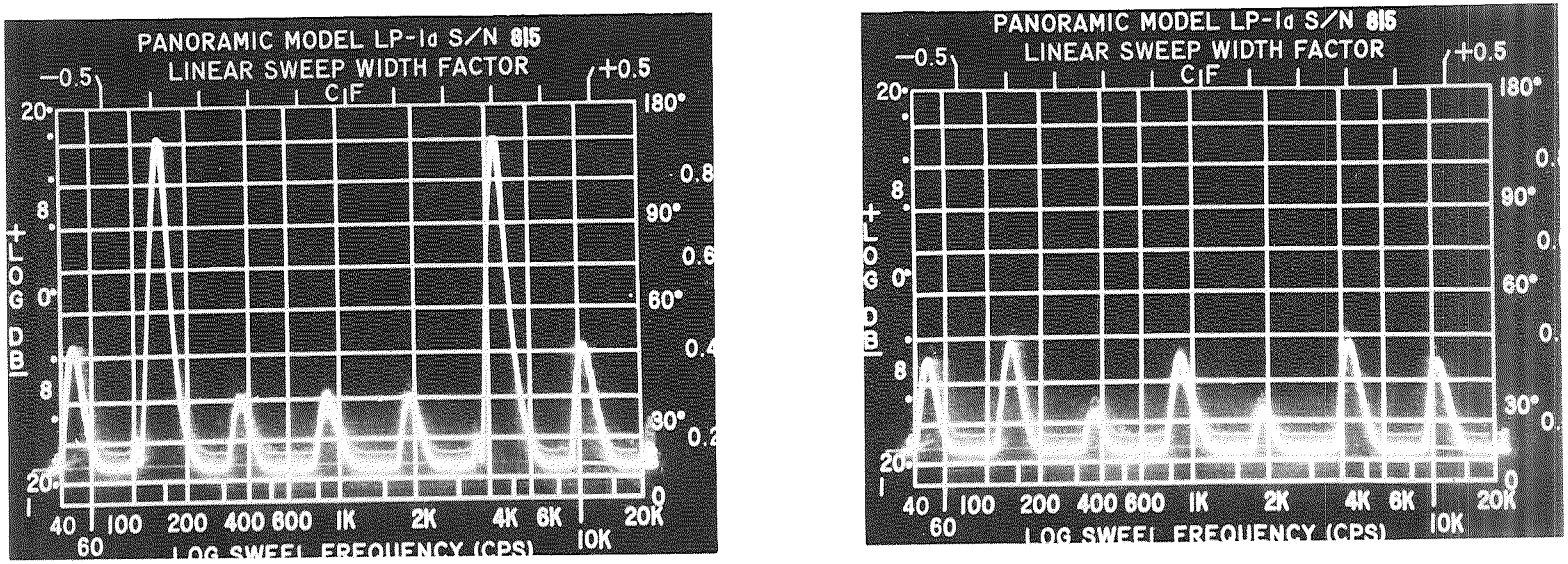



Figure 9. Testing with the improved resonant foam coupler system.




(a)
Debond

(b)
Good Bond

Figure 10. Bond condition indications obtained with an improved resonant foam coupler.

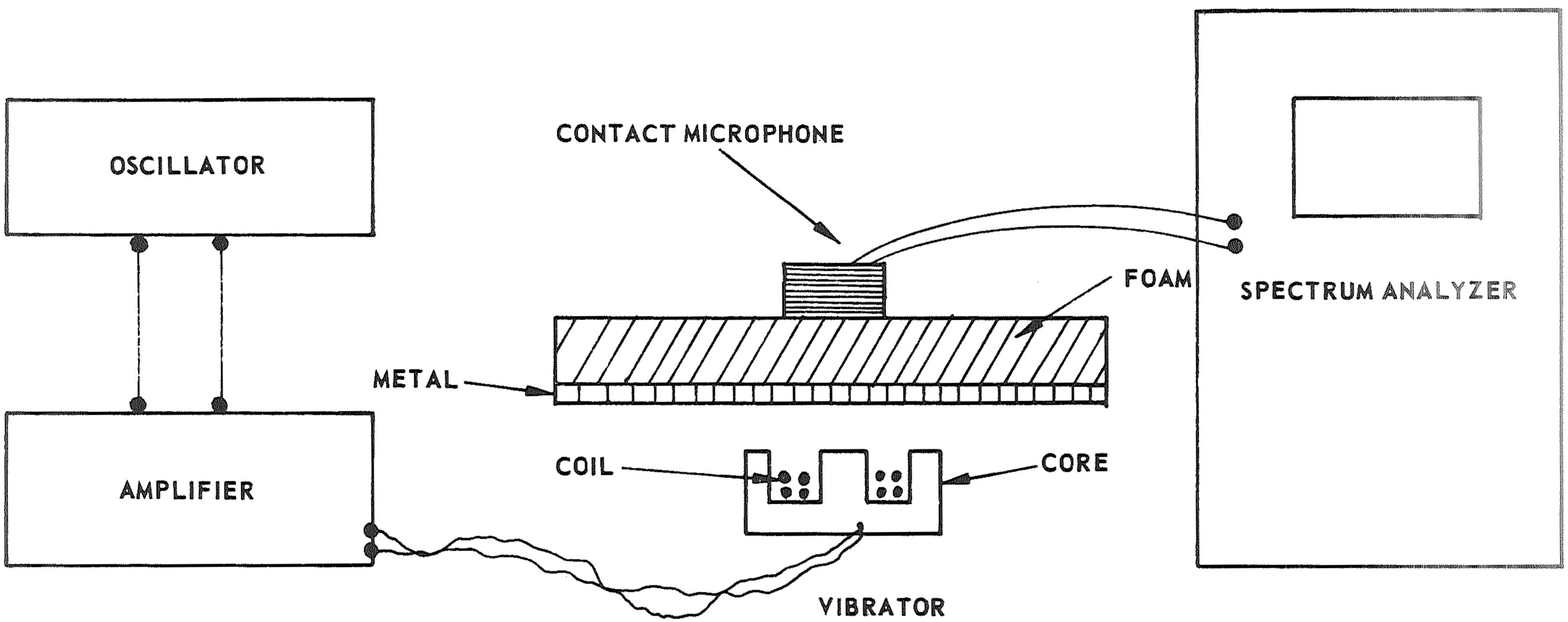



Figure 11. Details of a through-transmission eddy current system.

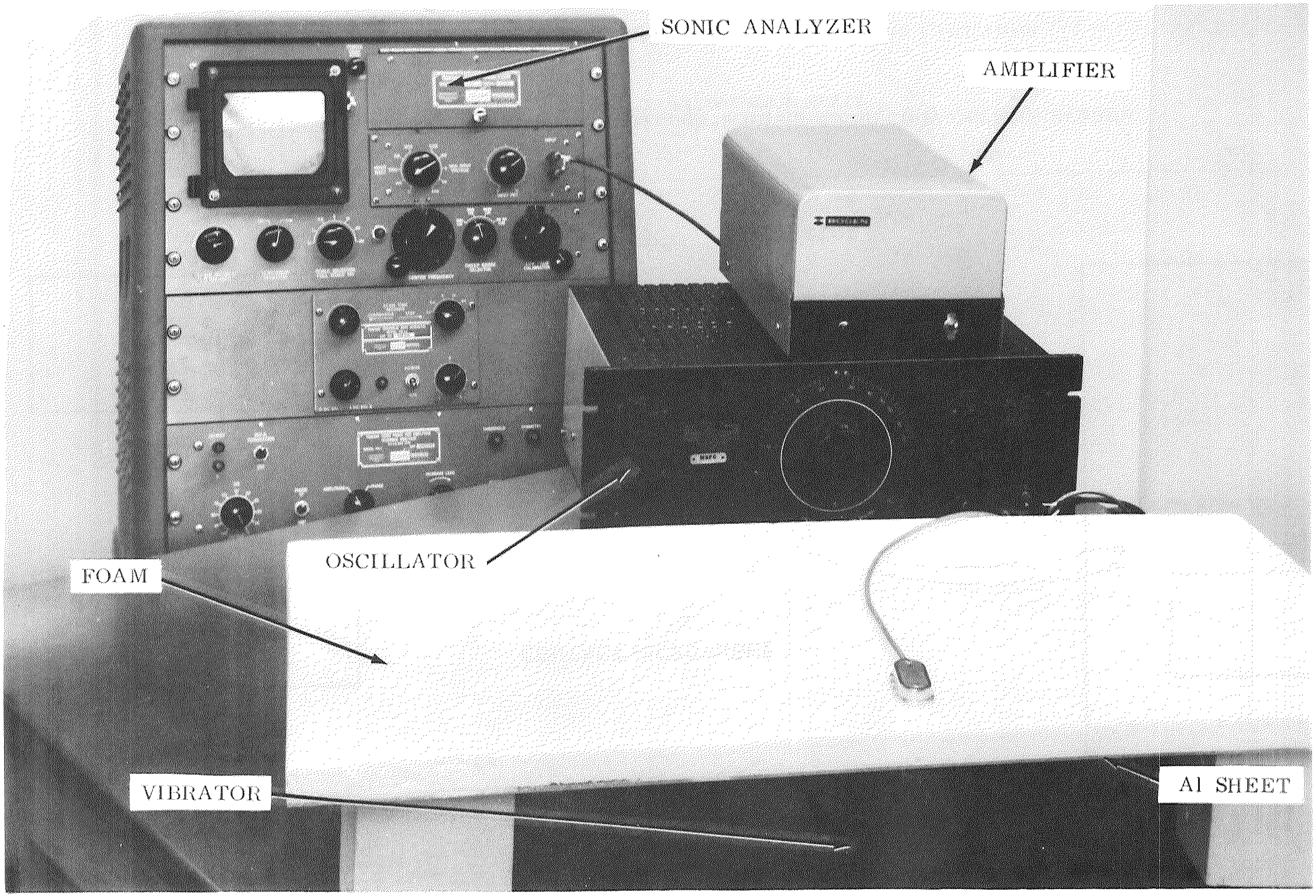



Figure 12. Through-transmission testing.

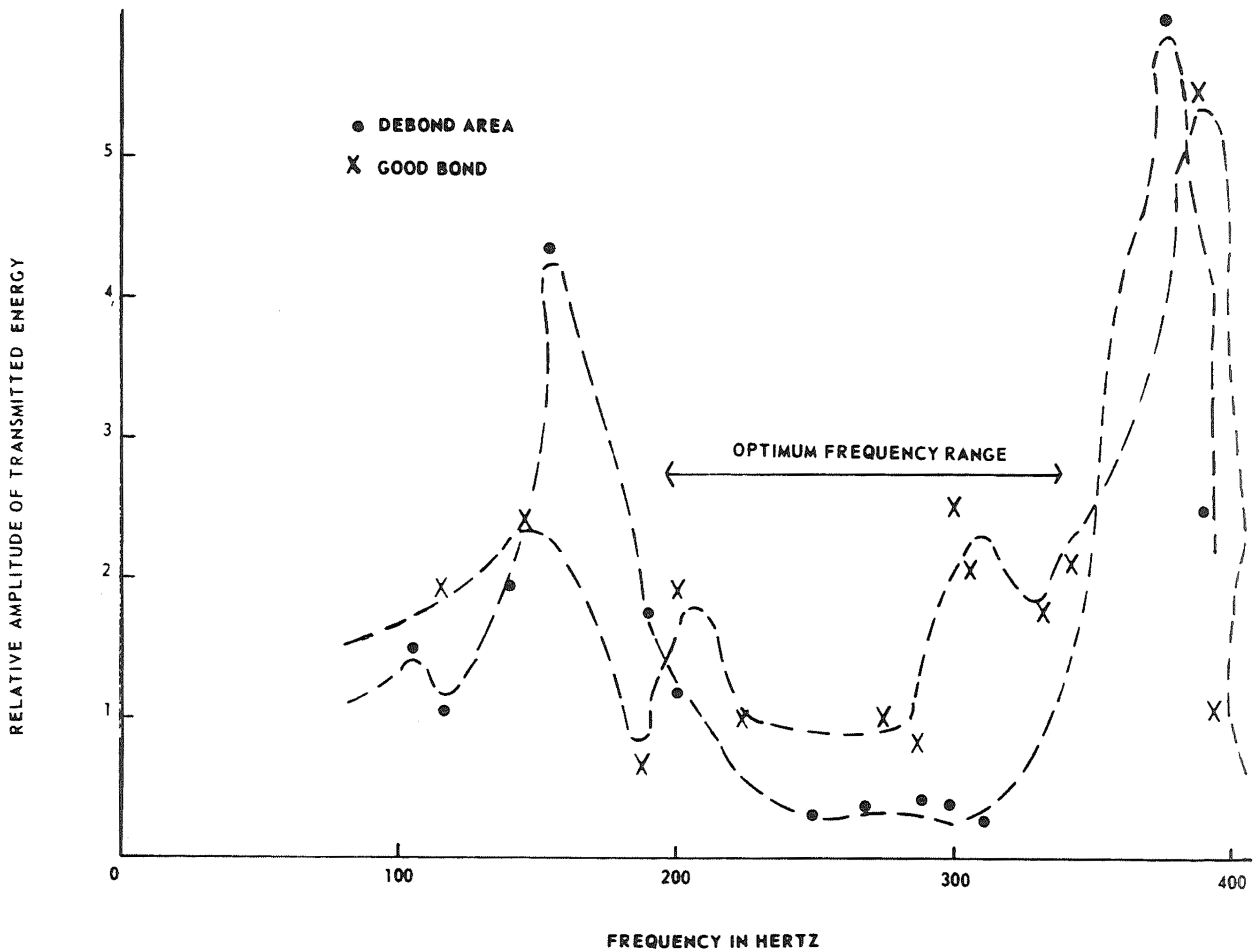
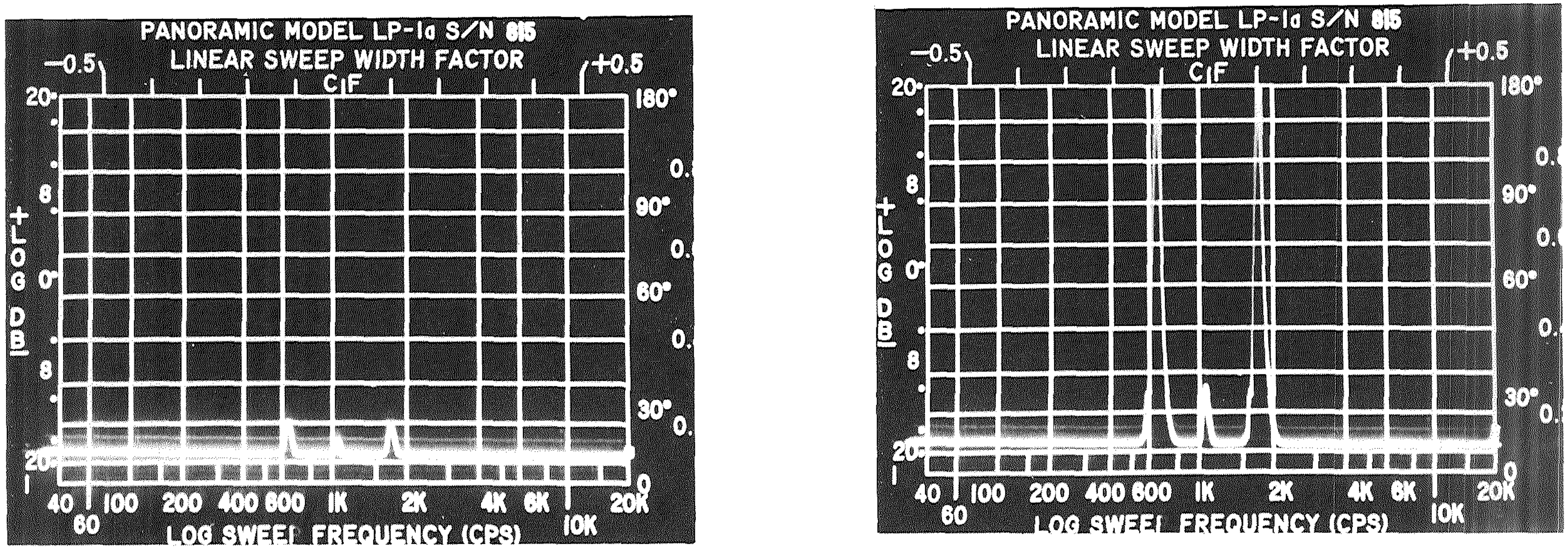



Figure 13. Frequency transmission characteristics of cryogenic insulation (NOPCO BX-250).




(a)
Debond

(b)
Good Bond

Figure 14. Bond conditions as indicated by the through-transmission eddy current method. (Low audio frequencies were used.)

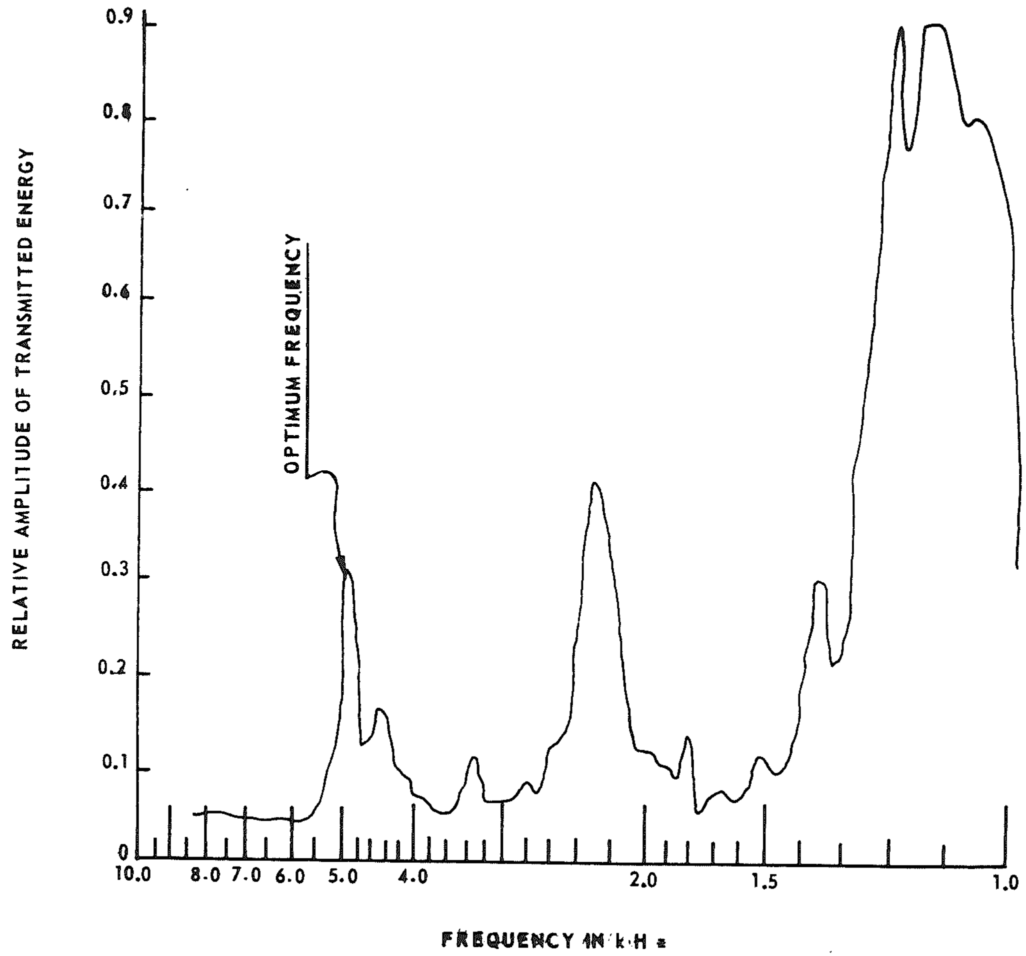



Figure 15. Transmission characteristics of well bonded cryogenic insulation (NOPCO BX-250).

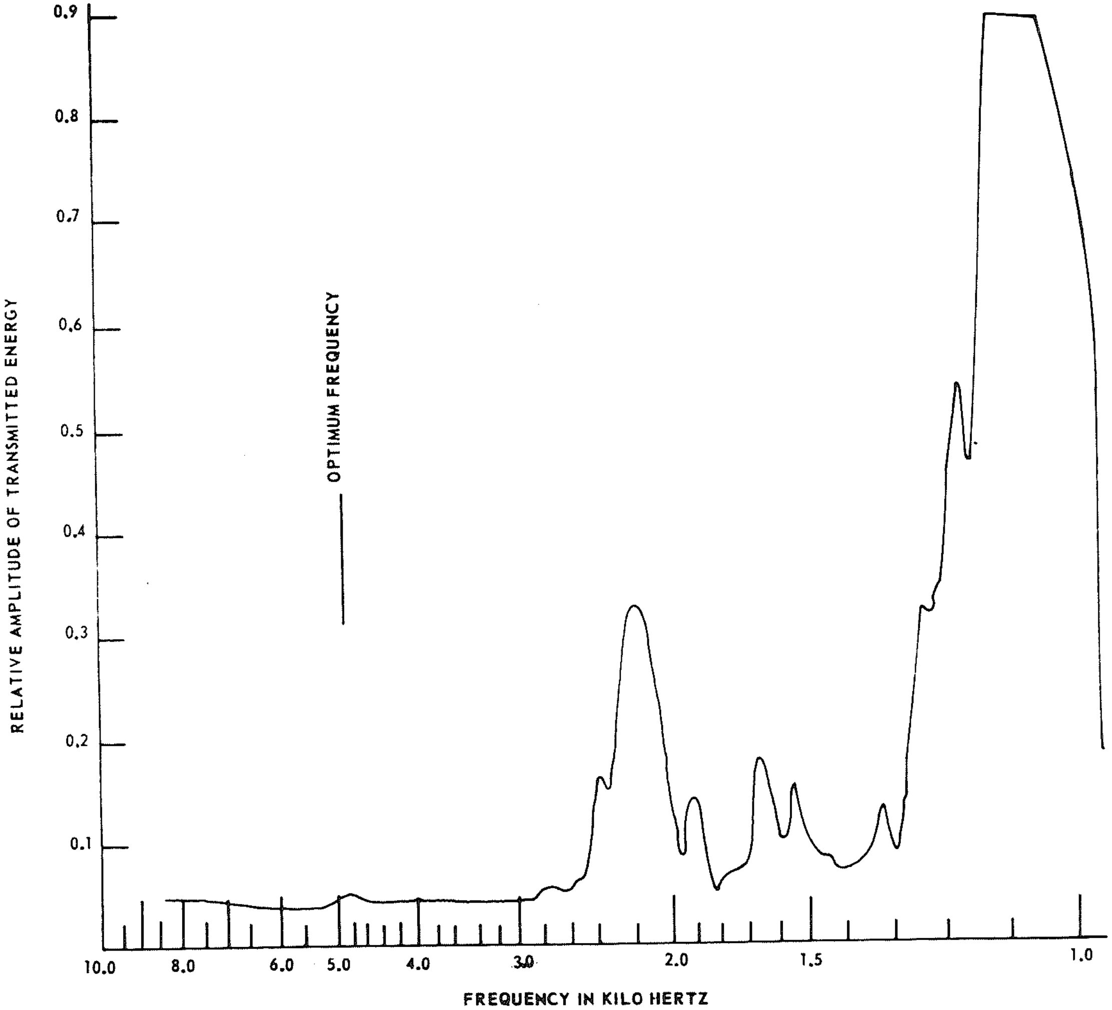
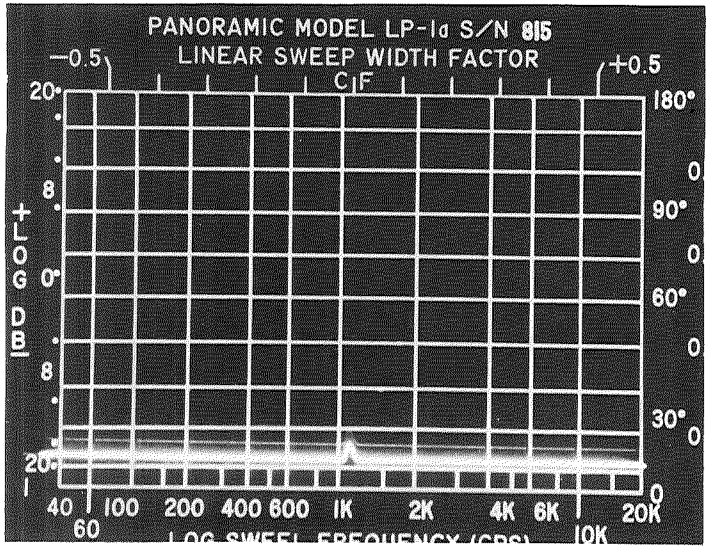
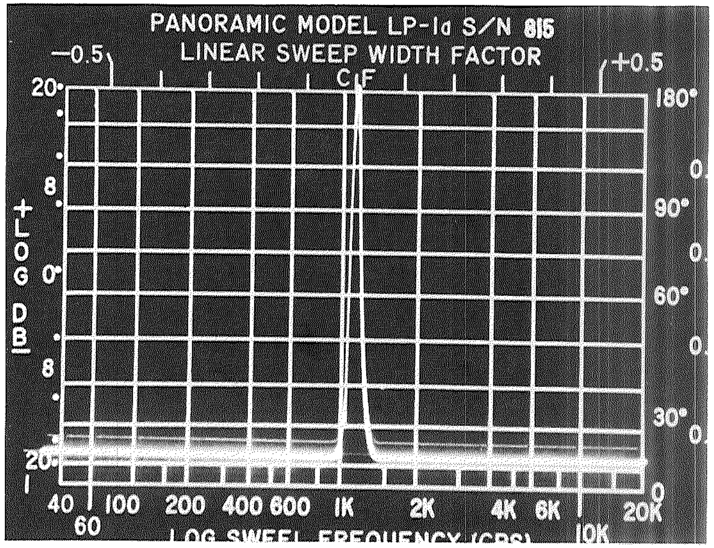



Figure 16. Transmission characteristics of a 3-inch debond in cryogenic insulation (NOPCO BX-250).

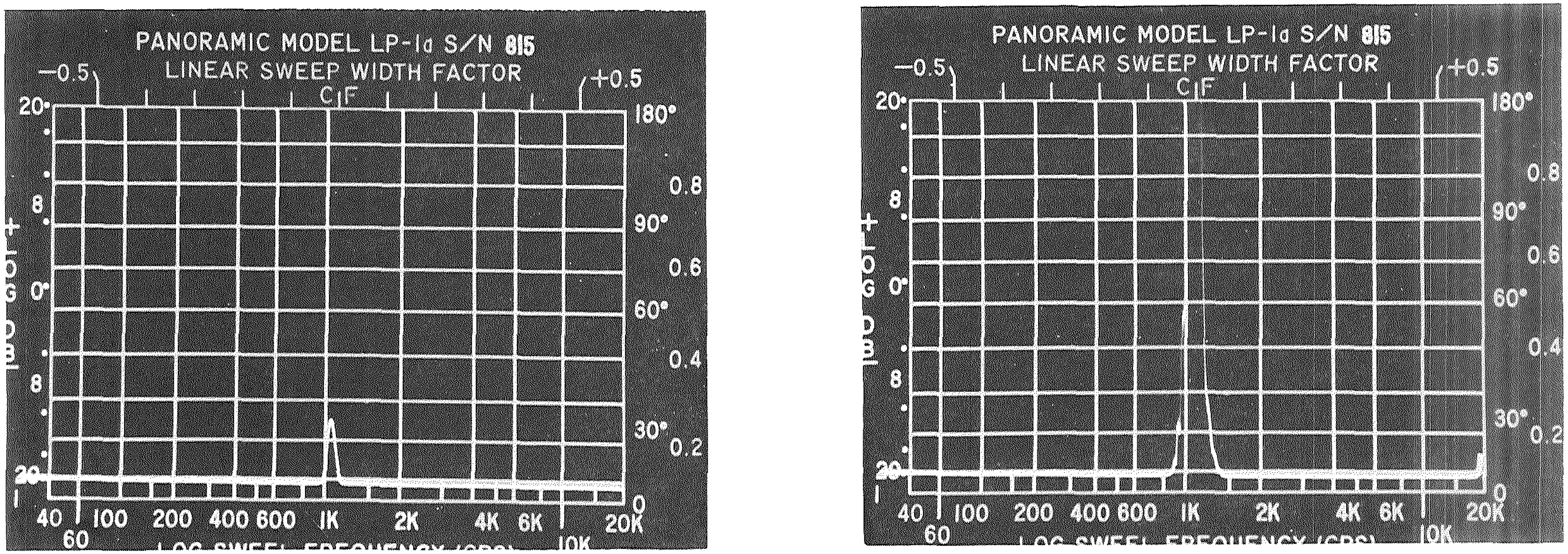



(a)
Debond




(b)
Good Bond

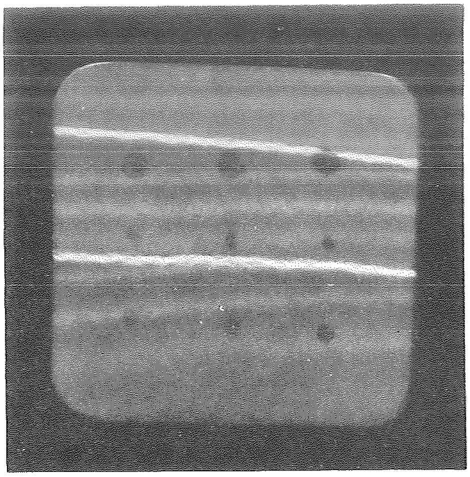
Figure 17. Bond conditions as indicated by the through-transmission eddy current method. (Higher audio frequencies were used.)



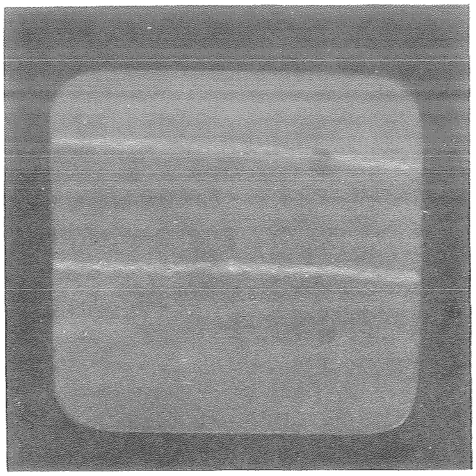

(a)
Void in Foam

(b)
Good Material

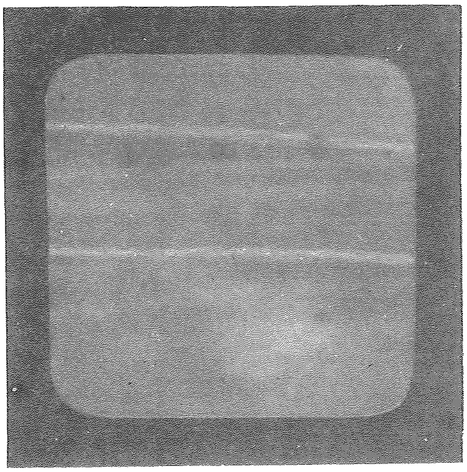
Figure 18. Through-transmission evaluation of void in foam-aluminum composite.



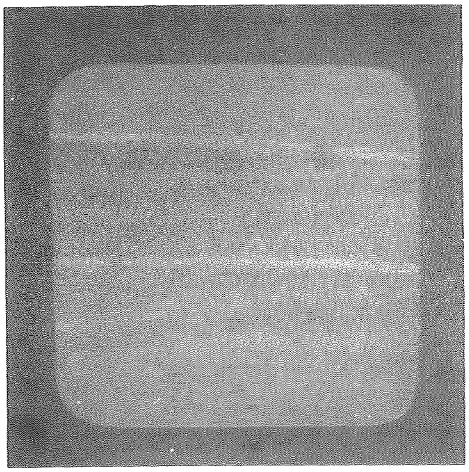
(a)
1-in. Foam
No Metal



(b)
1-in. Foam
0.063-in. Aluminum



(c)
1-in. Foam
0.125-in. Aluminum



(d)
1-in. Foam
0.188-in. Aluminum

Figure 19. Radiographic void detection in cryogenic insulation.

TM X-53940

# APPROVAL

## THE NONDESTRUCTIVE EVALUATION OF LOW DENSITY FOAM-ALUMINUM COMPOSITE MATERIALS

By W. N. Clotfelter, B. F. Bankston, and P. C. Duren

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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